Quantifying the Availability of TV White Spaces for Cognitive Radio Operation in the UK

Maziar Nekovee
BT Research, Polaris 134, Adastral Park,
Martlesham, Suffolk, IP5 3RE, UK
and
Centre for Computational Science, University College London
20 Gordon Street, London WC1H 0AJ, UK
maziar.nekovee@bt.com

June 18, 2009

Abstract

Cognitive radio is being intensively researched for opportunistic access to the so-called TV White Spaces (TVWS): large portions of the VHF/UHF TV bands which become available on a geographical basis after the digital switchover. Using accurate digital TV (DTV) coverage maps together with a database of DTV transmitters, we develop a methodology for identifying TVWS frequencies at any given location in the United Kingdom. We use our methodology to investigate variations in TVWS as a function of the location and transmit power of cognitive radios, and examine how constraints on adjacent channel interference imposed by regulators may affect the results. Our analysis provides a realistic view on the spectrum opportunity associated with cognitive devices, and presents the first quantitative study of the availability and frequency composition of TWVS outside the United States.

1 Introduction

Cognitive radio (CR) technology [1, 2] is a key enabler for the opportunistic spectrum access (OSA) model [11, 9], a potentially revolutionary new paradigm for dynamic sharing of licenced spectrum with unlicensed devices. In this operational mode a cognitive radio acts as a spectrum scavenger. It performs spectrum sensing over a range of frequency bands, dynamically identifies unused spectrum, and then operates in this spectrum at times and/or locations when/where it is not used by incumbent radio systems. Opportunistic spectrum access can take place both on a temporal and a spatial basis. In temporal opportunistic access a cognitive radio monitors the activity of the licensee in a given location and uses the licensed frequency at times that it is idle. An example of this is the operation of cognitive radio in the radar and UMTS bands. In spatial opportunistic access cognitive devices identify geographical regions where certain licensed bands are unused and access these bands without causing harmful interference to the operation of the incumbent in nearby regions.

Currently Cognitive radio is being intensively researched for opportunistic access to the so-called TV White Spaces (TVWS): large portions of the VHF/UHF TV bands which become available on a geographical basis after the digital switchover. In the US the FCC (Federal Communications Commission) proposed to allow opportunistic access to TV bands already in 2004 [3]. Prototype cognitive radios operating in this mode were put forward to FCC by Adaptrum, I^{2}R, Microsoft, Motorola and Philips in 2008 [12]. After extensive tests the FCC adopted in November 2008 a Second Report and Order that establishes rules to allow the operation of cognitive devices in TVWS on a secondary basis [13]. Furthermore, in what is potentially a radical shift in policy, in its recently released Digital Dividend Review Statement [4] the UK regulator, Ofcom, is proposing to "allow licence exempt use of interleaved spectrum for cognitive devices." [4]. Furthermore Ofcom states that "We see significant scope for cognitive equipments using interleaved spectrum to emerge and to benefit from international economics of scale" [4]. More recently, on February 16 2009, Ofcom published a new consultation providing further details of its proposed cognitive access to TV White Spaces [5].

With both the US and UK adapting the OSA model, and the emerging 802.22 standard for cognitive access to TV bands [6, 7] being at the final stage, we can expect that, if successful, this new paradigm will become

mainstream among spectrum regulators worldwide. However, while a number of recent papers have examined various aspects of cognitive radio access to TVWS in the United States [14, 15, 16, 17, 27, 18], there is currently very little quantitative information on the *global* spectrum opportunities that may result if CR operation in TV bands becomes acceptable in other countries in the world.

To bridge this gap, we present in this paper a quantitative analysis of TV White Spaces availability for cognitive radio access in the United Kingdom. Using accurate digital TV (DTV) coverage maps together with a database of DTV transmitters, we develop a methodology for identifying TVWS frequencies at any location in the UK. We use our methodology to investigate the variations in TVWS as a function of the location and transmit power of cognitive radios, and examine how constraints on adjacent channel emissions of cognitive radios may affects the results. Our analysis provides a realistic view on the potential spectrum opportunity associated with cognitive radio access to TWVS in the UK, and presents the first quantitative study of the availability and frequency composition of TWVS outside the United States.

The rest of this paper is organised as follows. In section II we discuss in detail the operation of cognitive radio devices in the VHF/UHF TV bands. This is followed by a description of our methodology for estimating TWVS frequencies. Section III presents results of our study of the availability of TVWS in 18 locations in the UK and analyses the implications of our findings. We conclude this paper in Section V.

2 Cognitive radio operation in TV bands

Broadcast television services operate in licensed channels in the VHF and UHF portions of the radio spectrum. The regulatory rules in most countries prohibit the use of unlicensed devices in TV bands, with the exception of remote control, medical telemetry devices and wireless microphones. In most developed countries regulators are currently in the process of requiring TV stations to convert from analog to digital transmission. This *Digital Switchover* is expected to be completed in the US in 2009 and in the UK in 2012. A similar switchover process is also underway or being planned (or is already completed) in the rest of the EU and many other countries around the world.

After Digital Switchover a portion of TV analogue channels become en-

tirely vacant due to the higher spectrum efficiency of digital TV (DTV). These cleared channels will then be reallocated by regulators to other services, for example through auctions. In addition, after the DTV transition there will be typically a number of TV channels in a given geographic area that are not being used by DTV stations, because such stations would not be able to operate without causing interference to co-channel or adjacent channel stations. These requirements are based on the assumption that stations operate at maximum power. However, a transmitter operating on a vacant TV channel at a much lower power level would not need a great separation from co-channel and adjacent channel TV stations to avoid causing interference. Low power unlicensed devices can operate on vacant channels in locations that could not be used by TV stations due to interference concerns [14]. These vacant TV channels are known as TV White Spaces, or interleaved spectrum in the parlance of the UK regulator. Opportunistic operation of cognitive radios in TV bands, however, is conditioned on the ability of these devices to avoid harmful interference to licensed users of these bands, which in addition to DTV include also wireless microphones [14]. In November 2008, the FCC adopted a report setting out rules allowing licence-exempt cognitive devices to operate in TV White Spaces. In summary these rules require cognitive devices to use a combination of spectrum sensing and geolocation. The devices must be able to sense both TV signals and wireless microphones down to -114 dBm, and must also locate their position to within 50 meters accuracy and then consult a database that will inform them about available spectrum in that location. Devices without geolocation capabilities are also allowed if they are transmitting to a device that has determined its location. Cognitive devices that use sensing alone are allowed in principle. However, the FCC states that such devices will be "subject to a much more rigorous approval process" [13].

The fundamental reason why TVWS have attracted much interest is an exceptionally attractive combination of bandwidth and coverage. Signals in TV bands, travel much further than both the WiFi and 3G signals and penetrate buildings more readily. This in turn means that these bands can be used for a very wide range of potential new services, including last mile wireless broadband in urban environments, broadband wireless access in rural areas [6, 7], new types of mobile broadband and wireless networks for digital homes. Furthermore, in the case of the UHF bands, the wavelength of signals in these bands is sufficiently short such that resonant antennas with sufficiently small footprint can be used which are acceptable for many

Figure 1: The available VHF and UHF TV spectrum in the UK after digital switchover, showing both the interleaved (TVWS) and cleared channels [4].

portable use cases and handheld devices [15].

3 Methodology

The digital TV standard adopted in the UK and the rest of Europe is DVB-T (Digital Video Broadcasting Terrestrial) which uses 8 MHz wide frequency bands for its transmission. This is unlike the US ATSC standard where each band is 6 MHz wide. Fig. 1 shows the chart of the UK's analog TV frequency bands and how these will be divided after digital switchover into cleared and interleaved spectrum [4]. From this chart it can be seen that the total UK interleaved spectrum, which is entirely in the UHF frequency range, is 256 MHz. However, Ofcom has proposed to auction off channels 61 and 62 for licenced use [23], reducing the TV bandwidth available for access by cognitive devices to a total of 240 MHz. However the exact number and frequency composition of TVWS can vary from location to location and is determined by the spatial arrangement of DTV transmitters and their nationwide frequency planning.

The CR transmission at a given location should not cause harmful interference to TV receivers both within the coverage area of nearby transmitters,

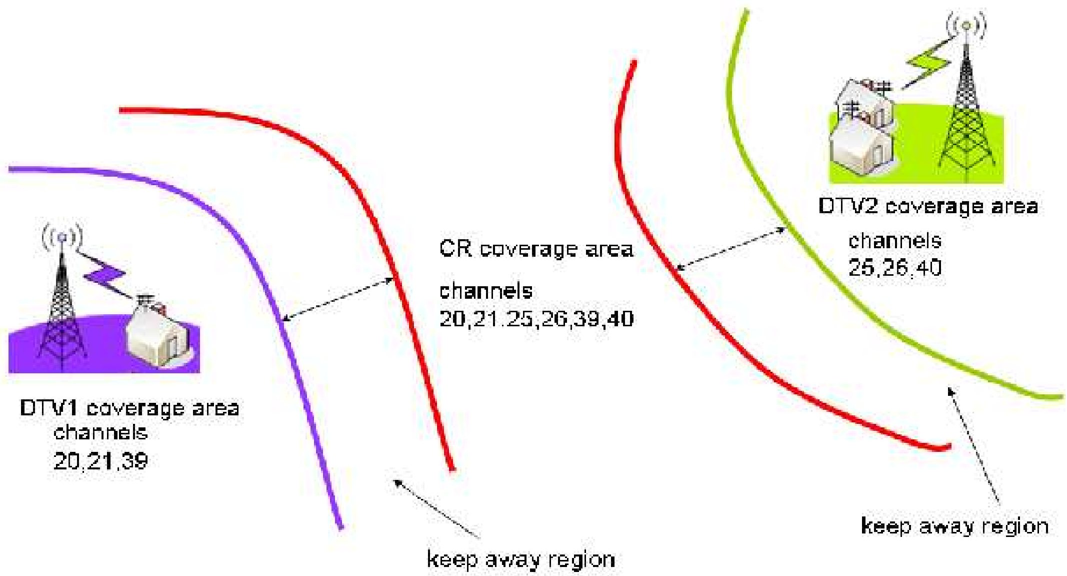

Figure 2: Opportunistic access to interleaved TV spectrum (White Spaces) by cognitive radios.

and at the edge of this area. To achieve this the CR device can transmit on the TV bands used by these transmitters only if its position is a minimum "keep-out" distance, R_{cr}, away from the edge of their coverage area [7]. Fig. 2 shows schematically a typical setup for the operation of a cognitive radio base station which operates in a given location in TV White Spaces which are available at that location.

In a simplified picture, based on the pathloss model [20], the keep-out distance can be obtained as follows. Denote with R_{tv} the maximum coverage radius of the TV station, and with P_{cr} and P_{tv} the transmit power of the TV transmitter and the CR transmitter, respectively. Then, in order to avoid interference with TV receivers that are at the edge of the coverage area, we must have:

$$\frac{P_{\rm tv}/R_{\rm tv}^{\alpha}}{P_{\rm cr}/R_{\rm cr}^{\alpha}} \geq \beta_{\rm th}, \tag{1}$$

where β_{th} is the sensitivity threshold of a TV receiver, and α is the pathloss

exponent. This yields:

$$R_{cr} \geq \left(\beta_{\text{th}} \frac{P_{\text{cr}}}{P_{\text{tv}}}\right)^{1/\alpha} R_{\text{tv}}. \tag{2}$$

Consequently, a CR device at location $\mathbf{r}$ can use the frequencies associated with a TV station located at $\mathbf{R}_j$ only if $|\mathbf{r} - \mathbf{R}_j| \geq R'_j$, where

$$R'_j = \left[1 + \left(\beta_{\text{th}} \frac{P_{\text{cr}}}{P^j_{\text{tv}}}\right)^{1/\alpha}\right] R^j_{\text{tv}}. \tag{3}$$

Repeating the above procedure for every TV transmitter, one can obtain the total number of TV transmitters whose associated frequencies can be used by a CR operating with a specified transmit power, P_{cr}, at location $\mathbf{r}$, from which the total number of TVWS frequencies available for opportunistic access, $\rho(\mathbf{r}, P_{cr})$, can be obtained as:

$$\rho(\mathbf{r}, P_{\text{cr}}) = \sum_j \sum_m \Theta(|\mathbf{r} - \mathbf{R_j}| - R'_j)\delta_{mj} \tag{4}$$

where Θ is the step function and $\delta_{mj} = 1$ if a frequency f_m is used by a DTV transmitter located at R_j and zero otherwise. Furthermore the first and the second sum in the above equation are over all DTV transmitters and all DTV frequencies, respectively.

In reality coverage contours of TV transmitters are far from circular due to a combination of terrain and clutter (building, trees, etc) diffraction of radio waves, non-isotropic radiation patterns of transmitter antennas, and interference resulting from nearby DTV transmitters [21]. Furthermore, shadow fading and atmospheric effects give rise to stochastic fluctuations in the received TV signal power [21]. In our study we make use of the publicly available maps of DTV coverage in the UK [22] which were generated via computer simulations from the Ofcom's database of location, transmit power (ERP), antenna height and transmit frequency of UK's 81 main DTV transmitters. These computer simulated coverage maps are further validated and refined through measurements and direct observation by DTV users. Fig. 3 shows, as an example, the coverage map of a DTV transmitter located in the vicinity of Oxford [22].

The typical transmit power of UK's DTV transmitters ranges between 25W and 200 kW (ERP) [24]. Consequently in the case of cognitive devices

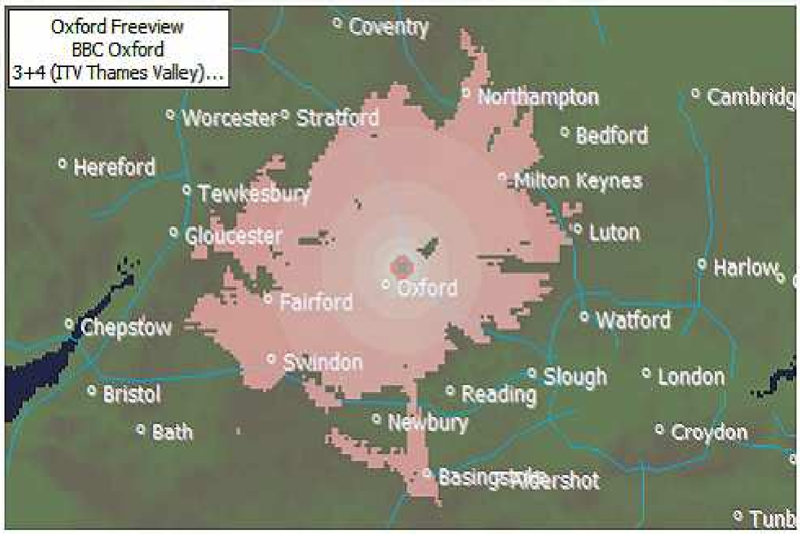

Figure 3: Coverage map of the DTV transmitter located near Oxford is shown. The square marks the location of the transmitter. The coverage area is shown in pink [22].

with transmit powers typical of licenced-exempt usage (~ 100 mW) we have $P_{CR}/P_{TV} \ll 1$. Consequently, in this low-power limit an *upper bound for* the vacant TWVS frequencies at a given location can be directly extracted from the coverage maps of DTV transmitters, as can also be seen from Eqs.(3-4).

Our computer algorithm for obtaining such upper bounds works as follows. We use the UK National Grid (NG) coordinate system [25] in order to specify the geographical position of any location on the UK map. Given the NG coordinates of a UK location our code then maps this location onto the closest grid point on the coverage maps of DTV transmitters. For a given DTV transmitter this grid point is then evaluated to determine if it falls within the coverage area of that transmitter. If this is the case, then the frequencies associated with the transmitter are tagged as *occupied* at that location, otherwise they are tagged as *vacant*. Repeating this procedure for coverage maps of the entire 81 UK transmitters, we then obtain a list of vacant TV frequencies at a given location that can be used by a low-power cognitive device which is positioned in that location.

In the case of high power cognitive equipments, e.g. those considered within the 802.22 standard with transmit powers as high as 4 Watts (ERP)

[7], the keep-out radius associated with a cognitive radio is substantial, e.g. between $30 - 120$ km. This keep out radius need to be taken into account when estimating vacant TV frequencies at a given location. However, due to the irregular shape of TV coverage contours the required computations are very intensive. In order to reduce this computational effort, we have approximated the actual DTV coverage areas by circular disks centred at a each DTV transmitter. These disk were constructed such that each of them entirely encompassed the coverage area of the associated transmitter while also having the minimum possible surface area. With this simplification, it is then computationally straightforward to calculate from Eqs. (3-4) the vacant TV frequencies as a function of both position and transmit power of cognitive devices.

4 Results

Potential applications of TVWS devices will strongly depend on how the availability of this spectrum varies, both from location to location and as a function of transmit power of cognitive devices. The FCC, for example, is considering two classes of uses cases. The first corresponds to fixed devices with relatively high transmit power, line of sight operation and ranges up to 30 km. One expected use case for this class is broadband wireless access to rural areas, for which the IEEE 802.22 standard is being developed. A second class of use cases under consideration by the FCC are those associated with personal/portable devices which maybe nomadic or mobile [15]. In the rest of this paper we shall focus mainly on use cases corresponding to low-power cognitive access. A full analysis for the case of high transmit power devices will be presented elsewhere.

4.1 TVWS availability and frequency composition

Fig. 4 summarises in a bar-chart the availability of TVWS channels for 18 major population centres in England, Wales and Scotland. The total number of channels available at each location is shown as red bar. It can be seen that there are considerable variations in the number of TVWS channels as we move from one UK location to another. For any given location, however, a minimum of 12 channels (96 MHz) are accessible to low-power cognitive devices, while the average available spectrum is just over 150 MHz.

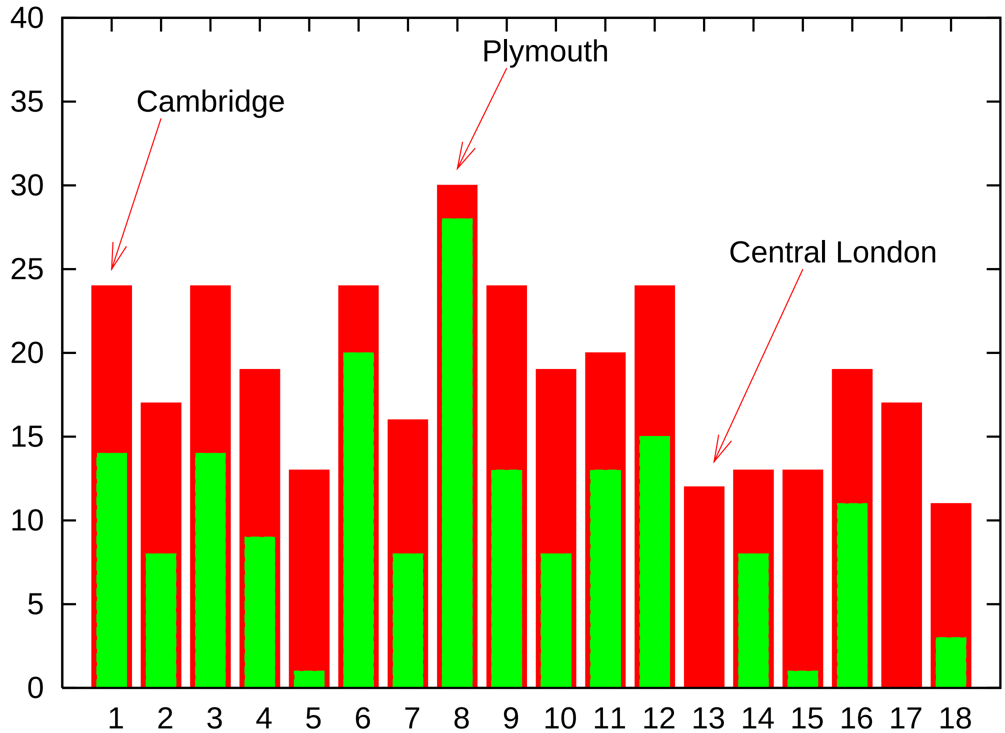

Figure 4: Variations in the availability of TV White Spaces is shown for 18 UK locations. Results are shown before (red bars) and after (green bars) the exclusion of those vacant channels whose adjacent channels were found to be occupied by DTV transmission.

In addition to estimating total available TVWS, it is of importance to investigate channel composition of this spectrum. In Fig. 5 we show, as an example, channel composition of TVWS in 4 cities in England: Bristol, Liverpool, London and Southampton. In this Figure vacant channels are shown as blue bars while occupied channels are left blank. As can be seen from the figure, the precise composition of TVWS channels vary greatly from location to location. In particular, both in Bristol and Liverpool most of the available channels are located in the lower end ($470 - 550$ MHz) of the UHF band while in the case of Southampton these channels are bunched up in the higher end of this band ($630 - 806$ MHz). Furthermore, the available TVWS channels can be highly *non-contiguous*. This feature may greatly restrict access to TVWS by most current wireless technologies, as modulation

schemes implemented in these technologies often require a contiguous portion of the spectrum. In the case of London, for example, although a total of 96 MHz spectrum is in principle available, only 16 MHz can be utilised for contiguous frequency access.

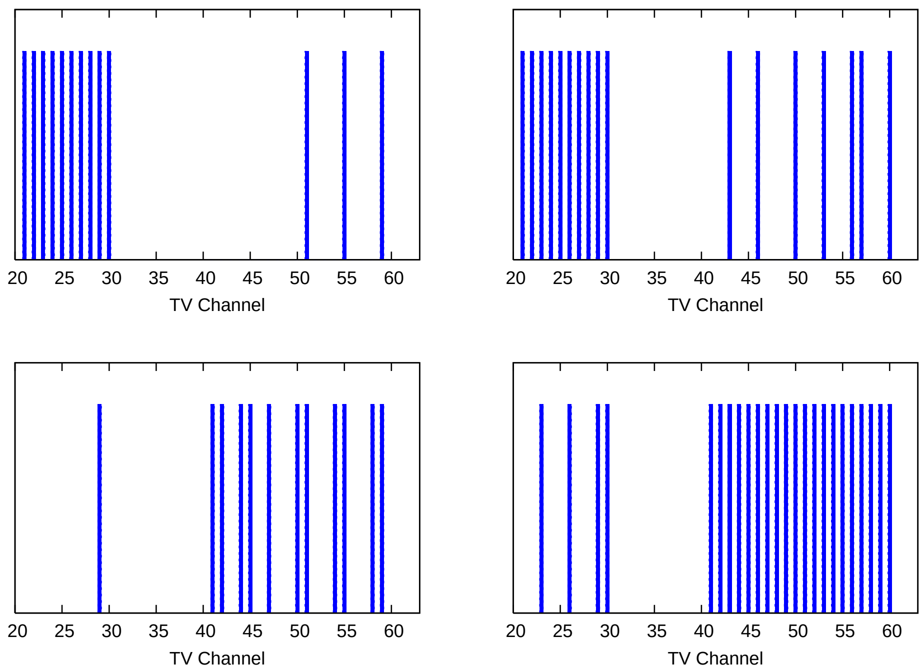

Figure 5: The availability of TV White Space frequencies for low power cognitive radios are shown, from left to right and top to bottom, in Bristol, London, Liverpool and Southampton. Channels available for cognitive radio are shown as blue bars.

4.2 The impact of adjacent channel interference and transmit power

When a high power cognitive device operates in a vacant TV channel, energy leakage to adjacent channels may cause interference to TV sets that are tuned to these adjacent frequencies. To eliminate the occurrence of such adjacent-channel interference the IEEE 802.22 Working Group prescribes that if channel N is occupied by an incumbent, then cognitive devices should

not only vacate this channel but they also should refrain from transmitting at channels $N \pm 1$. In addition, in the UK Ofcom has raised concerns that operation of low-power cognitive devices on a given channel may also cause adjacent-channel interference for mobile TV receivers that are in close vicinity. Consequently, even in such low-power use cases, cognitive devices may be be constraint not to use vacant channels whose immediate adjacent frequencies are used for mobile TV. It is therefore of considerable interest to investigate how imposing such constraints will affect the availability of TVWS spectrum.

The total number of available TVWS after imposing the above adjacent channel constraint are shown as green bars in Fig. 6. These results are obtained by eliminating from the list of TVWS channels any vacant channel whose immediate adjacent channels were found occupied. It can be seen that imposing the constraint drastically reduces the amount of accessible spectrum in most locations considered. In particular, in the case of central London we see that with this constraint imposed there will be *no channel* available for the operation of CR devices. Averaging the results over all locations, we find that with this constraint imposed there will be only ~ 30 MHz of TV spectrum available for cognitive access.

Finally, we use the estimation approach outlined in Section III to briefly examine the impact of cognitive radio transmit power on the the availability of TVWS channels. Fig. 7 shows, as an example, variations in the number of vacant TV channels as a function of CR transmit power in the case of Manchester [26]. It can be seen that for $p_{cr} \leq 100$ mW up to 17 channels (136 MHz) are available. However, the availability decreases sharply as the transmit power is increased beyond this range. Nevertheless, there is still 40 MHz of spectrum available for CR device transmitting at 2 W, within the typical operation of future 802.22 devices.

5 Conclusions

In this paper we presented a methodology for estimating the UK TV White Spaces for opportunistic access by cognitive radios. Using our methodology we examined the availability of this spectrum and its channel composition in 18 UK population centres. Our analysis shows on average ~ 150 MHz of TVWS is available for access by low-power cognitive radios. We found, however, that in many locations this considerable bandwidth is fragmented

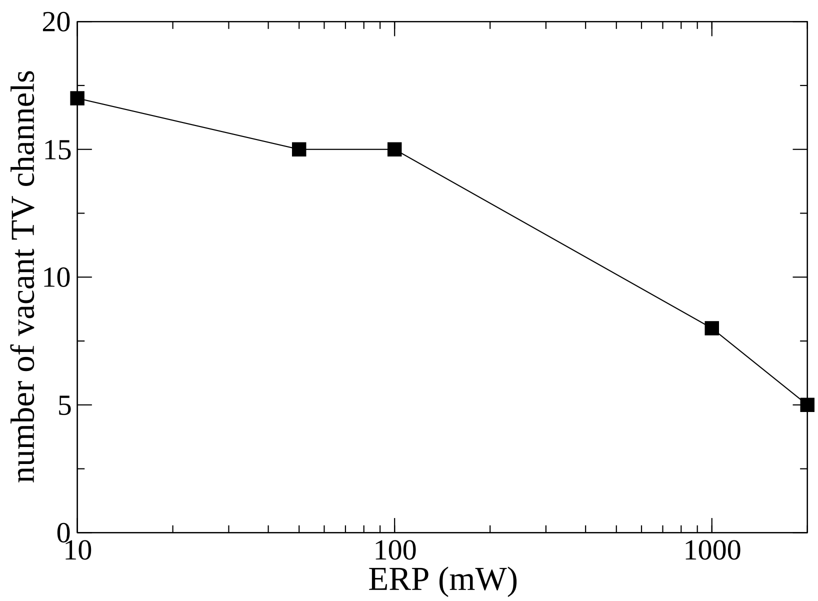

Figure 6: Variation in the number of TVWS channels is shown as a function of transmit power, computed for the city of Manchester.

into many non-adjacent channels. Consequently, we conclude that the availability of novel pooling techniques, such as NC-OFDM [27, 28] is crucial for effective utilisation of TVWS, in particular for future high bandwidth applications. Finally, we examined the effect of constraints on adjacent channel interference imposed by regulators/standards on TVWS, and showed that such constraints drastically reduce the availability of this spectrum.

Most future use scenarios of TVWS will involve multiple cognitive devices operating within the same geographical region [29]. Some of our future work will focus on new methodologies for estimation and control of *aggregated* cognitive radio interference in such scenarios. We are also working on improved TVWS estimation methods for high power use cases.

Acknowledgements

The author is grateful to Brian Butterworh (UK Free.TV) for providing access to his DTV coverage data, and to Keith Briggs (BT), Yang Fang and Anjum Pervez (South Bank University) for their valuable contributions.

References

[1] J. Mitola Cognitive radio for flexible mobile multimedia communications. In the Sixth international Workshop on Mobile Multimedia Communications, San Diego, CA, 1999.

[2] S. Haykin, Cognitive radio: Brain-empowered wireless communications, IEEE Journal on Selected Areas in Communications, Vol 23, No. 2, pp 201-219, 2005.

[3] First report and notice of rulemaking in the matter of unlicensed operation in TV broadcast bands, ET Docket No. 04-186, Adopted October 18, 2006.

[4] Ofcom, Digital Dividend Review, A statement on our approach to awarding the digital dividend, 13 December 2007.

[5] Ofcom, Digital dividend: cognitive access, 16 February 2009.

[6] IEEE 802.22 Working Group on Wireless Regional Area Networks, www.ieee802.org/22.

[7] C. Cordeiro K. Challapali, D. Birru IEEE 802.22: An introduction to the first worldwide wireless standard based on cognitive radios, Journal of Communications, Vol 1, No 1, pp 38-47, 2006.

[8] M. Nekovee, Dynamic spectrum access – concepts and future architectures, BT Technology Journal, Vol 24, No 2, pp 111-116, 2006.

[9] M. Nekovee, Impact of cognitive radio on future management of spectrum, Proc. CrownCom 2008, Singapore, May 2008.

[10] M. Nekovee, Dynamic spectrum access with cognitive radio: architectures and research challenges, Proc. CrownCom2006, Mykonos, Greece, May 2006.

[11] W. D. Horne, Adaptive Spectrum Access: Using the full spectrum space, Technical Report, The MITRE Corporation, 2004.

[12] The FCC's Office of Engineering and Technology release report on test of prototype white space devices, ET Docket No. 04-186, available from www.fcc.gov.

[13] FCC adopts rules for unlicensed use of Television white spaces, Official announcement of FCC, November 4, 2008, available from www.fcc.gov.

[14] M. A. Stuzra and F. Ghazvinian, Can cognitive radio technology operating in the TV white spaces completely protect licensed TV broadcasting?, Working paper No 16, Wireless Future Program, New America Foundation.

[15] F. L. Martin, N. S. Correal, R. L. Eki, P. Gorday and R. O'Dea, Early opportunities for commercialisation of TV whitespaces in the U.S, Proc. CrownCom 2008, May 2008, Singapore.

[16] M. Petty *et al.* Feasibility of dynamic spectrum access in underutilized TV bands, Proc. IEEE DySpan 2007, Dublin, Ireland, April 2007.

[17] T. X. Brown and D. C. Sicker, Can cognitive radio support broadband wireless access? Proc. IEEE DySPAN 2007, Dublin, Ireland, April 2007.

[18] Geo-location database technique for incumbent protection in TV White Spaces, D. Gurney, G. Buchwald, L. Ecklund, S. Kuffner, and J. Grosspietsch, Proc. IEEE DySPAN 2008, October 2008, Chicago, USA.

[19] Cognitive radio system using IEEE 802.11a over UHF TVWS, R. Ahuja, R. Corke, A. Bok, Proc. IEEE DySPAN 2008, October 2008, Chicago, USA.

[20] T. Rappaport, *Wireless Communications, Principle and Practice*, Prentice-Hall, 2000.

[21] DTT coverage predictions – how they are made and tested, I. Pullen, Digital News, No. 9, July 1999, pp 14-15.

[22] UK FREE.TV website at *www.ukfreetv.tv.*

[23] Ofcom, Digital Dividend Review: Consultation on geographic interleaved awards $470 - 550$ MHz and $630 - 790$ MHz, 12 June 2008.

[24] Ofcom, Digital switchover transmitter details *www.ofcom.org.uk/tv/ifi/tech/dsodetails/81plan.pdf.*

[25] *www.ordancesurvey.co.uk*

[26] Y. Fang, Estimation of available digital TV channels for cognitive radio operation, MSc. Final Report, Telcommunication and Network Engineering, London South Bank University, 2008.

[27] J. D. Person and W. D. Horne, Discontiguous OFDM considerations for dynamic spectrum access in idle TV bands, Proc. IEEE DySPAN 2005, Baltimore, Maryland, USA, 2005.

[28] R. Rajbanshi, A. Wyglynski and G. Minden, An efficient implementation of NC-OFDM transceivers for cognitive radios, Proc. CrownCom 2006, Mykonos, Greece, 2006.

[29] N. S. Shankar and C. Cordeiro, Analysis of Aggregated Interference at DTV receivers in TV bands, Proc. CrownCom 2008, May 2008, Singapore.